Between Performance and Complexity: G. David Forney, Jr., and the Utility of Information Theory

By Alexander B. Magoun

During his career, G. David Forney, Jr. (Fig. 1) has sought to develop or refine practical techniques to reach the "Shannon limit"—namely, the maximum data rate possible on a given communication channel. Attaining such an ideal invariably requires tradeoffs, a balance, between performance and complexity. For the technology of a particular moment and the user of a particular channel, what is the most effective or sophisticated code available to maximize that data rate?

Forney addressed this question in various ways in his long career, both in an industrial context at Codex Corporation, the startup company in Cambridge, MA, USA, that he joined after his doctorate at MIT, and in his many published papers. The answers that he and his colleagues arrived at often influenced the field of information theory, as well as the survival and success of Codex.[1]

This month's historical article takes a look at G. David Forney Jr.'s work in improving commercial modem efficiency through blends of information theory and electrical engineering.

I. Saving a Company With Information Theory, 1969–1971

Nineteen seventy was an awful year for Dave Forney and his employer, for "everything bad that could ever possibly happen to a company happened to Codex Corporation."[2] Following a federal budget cut, Codex's military contracts dropped in number from 14 to nine, slicing income by 75%.[3] Gone was the million-dollar satellite communications contract that the perpetually optimistic cofounder and president, James Cryer, was convinced would be renewed. Gone was the followup contract to the sequential decoder that Forney had designed and developed in 1969. Gone were more than half of the 200 employees, as Codex's share price plummeted from nearly $50 to $3 and executives begged its bank for funds to cover payroll.[4] Its first commercial product, a high-speed modem, turned out to be a servicing nightmare that lost money on every sale. Arthur Kohlenberg, a cofounder and Forney's mentor, lost a long struggle with Hodgkin's disease in July. Finally, on the day before a closing with Kuhn, Loeb & Company in April to obtain a desperately needed line of credit, Cryer died while playing tennis.

[1] This article is a continuation of A. B. Magoun, "From theory to practice: G. David Forney, Jr. and the innovation of information theory," *Proc. IEEE*, vol. 106, no. 5, pp. 1006–1009, May 2018. For more on Forney's intellectual interests, see R. Blahut and Ralf K., eds., *Codes, Graphs, and Systems: A Celebration of the Life and Career of G. David Forney, Jr. on the Occasion of his Sixtieth Birthday*. New York, NY, USA: Springer Science & Business Media, 2002).

[2] G. David Forney, Jr., an oral history conducted in 1995 by Andrew Goldstein, IEEE History Center, http://ethw.org/Oral-History:G._David_Forney#The_Modem_Business_and_the_AE-96. Unattributed quotations are from this oral history.

[3] Codex military contracts for Fiscal Year 1967–1968: 9 for $550 000–$743 000; 1968–1969: 14 for $1 400 000–$2 736 000; 1969–1970: 9 for $315 000–$641 000: Records of Prime Contracts Awarded by the Military Services and Agencies, created July 1, 1965 – June 30, 1975, Office of the Assistant Secretary of Defense (Comptroller), Office of the Deputy Assistant Secretary (Management Services), Directorate for Information Operations and Control (ca. 1973 – 10/01/1977), Records of the Office of the Secretary of Defense, Record Group 330, U.S. National Archives, https://aad.archives.gov/aad/series-description.jsp?s=492, accessed Aug. 30, 2018.

[4] J. Pelkey, "Codex Selected Balance Sheet," www.historyofcomputercommunications.info/Organizations/Startups/Codex/CodexSelectedBalanceSheet.pdf, accessed Aug. 31, 2018.

Digital Object Identifier 10.1109/JPROC.2018.2872641

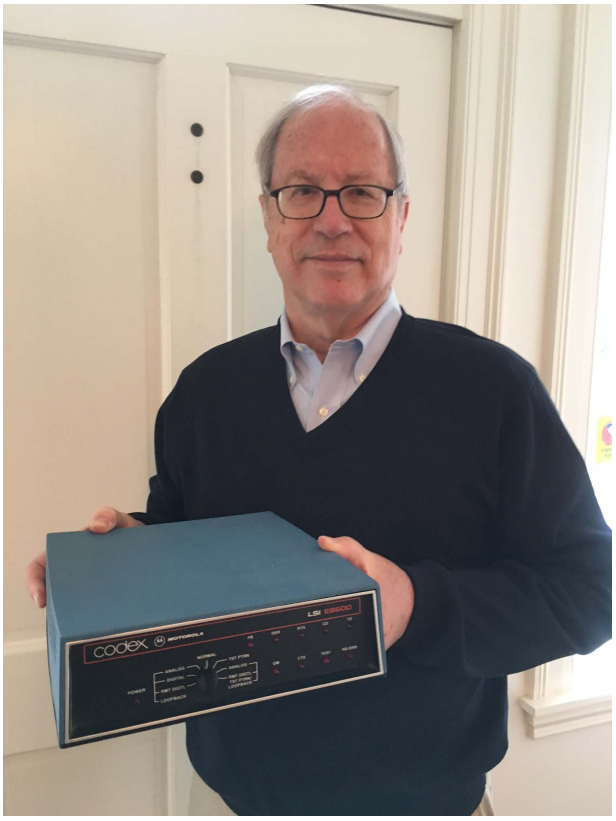

Fig. 1. *Dave Forney holds one of the Codex LSI E9600 modems which sold for $2650 when it debuted in October 1982. This was nearly one tenth of the price of Codex's first 9600-b/s modem, the AE-96, in 1969. (Courtesy of IEEE.tv. https://ieeetv.ieee.org/technology/dave-forney-ieee-medal-of-honor-2016?.)*

Only two years earlier, the strategy of moving into digital telecommunications hardware had seemed extremely promising. Under Cryer's impetus, the company planned to exit the small and erratic government error-correction business for which Forney had been hired out of MIT's Information Theory group: "we were all by ourselves, and there was a very good reason . . . there wasn't any business there." Instead, Codex would begin extending digital data communications to commercial industries through a revolutionary piece of hardware. In 1968, IBM and DEC were selling mainframes and minicomputers as fast as they could make them, commercial time-sharing of those computers was accelerating, and the computers in conglomerating corporate divisions and offices needed high-speed connections to remote job entry (RJE) terminals.[5]

To that end, Codex hired Jerry Holsinger, an MIT classmate of Forney's, to commercialize the 9600 bits per second (b/s) single-sideband modem with adaptive equalization that he had been designing in California for the National Security Agency's secure speech system.[6] It also hired manufacturing and sales directors to complete the innovation process as a commercial product. In May 1968, Codex introduced the AE-96. The first commercial modem to operate at 9600 baud, four times AT&T's standard modem data rate, it was "ugly as sin, because it had a military package," and weighed nearly 60 kg, contained 122 circuit boards of RTL logic, and sold for $23 000 apiece. After landing a million-dollar Air Force satellite communications contract,[7] Codex went public in late September with an initial offering of 135 000 shares priced at $17 per.[8] However high that seemed to Forney, it was a bargain when the value nearly tripled over the next year.

By 1969, however, the AE-96 proved to be exceedingly problematic for the few commercial customers, largely airlines and banks, who were equipped to transfer data at such a speed. The inside joke was that Codex "sold a total of 300 of them. . .. which went out three times and came back twice. It was very hard to make them stick because they were just marginal performers, marginally reliable."[9] Beyond the primitive nature of the device as a manufactured product, the modem had multiple technical problems, some of which Holsinger solved before leaving the company in the fall.[10]

An unsolved issue was the modem's single-sideband architecture for "partial response" with sidetones, which lost 3 dB in signal-to-noise ratio (SNR) margin. Forney began to engage with the AE-96 at Kohlenberg's request to "become a modem expert."[11] This was a new field for Forney, but once he understood the issue, "I thought there ought to be a way that you could use the information over more than one symbol to make better decisions. . .. I worked out what looked to me would be the optimum way to make a decision for partial response, and later generalized that."[12] Senior design engineer Al Berner built Forney's circuit and installed it in a drawer hanging from the lid of the modem because there was no space on the

[5]The 1968 Federal Communications Commission (FCC) order ending AT&T's monopoly on equipment attached to its telephone network—the "Carterfone decision"—had no effect on Codex's change in strategy because it applied to the public switched telephone network and Codex focused on private leased lines.

[6]J. L. Holsinger, "Data transmission method and system," U.S. Patent 3,614,622, filed Apr. 30, 1968.

[7]Military Prime Contract File 7/1/1968–6/30/1969, Records of Prime Contracts Awarded by the Military Services and Agencies, *op. cit.*, https://aad.archives.gov/aad/recorddetail.jsp?dt=214&mtch=14&cat=GS29&tf=F&sc=873,838,869,856,857,858,859,860&q=codex&bc=,sl,fd&rpp=10&pg=2&rid=40469&rlst=40467,40468,40469,40470, accessed Aug. 30, 2018.

[8]"Codex Corp. to Sell Stock," *SEC News Digest*, Sep. 27, 1968, p. 6.

[9]Art Carr, Codex's vice president for marketing, recalled that the company "only sold and made stay 70 some AE-96s." Interview of A. Carr by J. M. Pelkey, Apr. 6, 1988, CHM ref. no. X5671.2010, p. 14, http://archive.computerhistory.org/resources/access/text/2015/10/102737982-05-01-acc.pdf, accessed Aug. 31, 2018.

[10]Interview of J. L. Holsinger by J. M. Pelkey, Apr. 6, 1988, CHM ref. no. X5671.2010, p. 6–7, http://archive.computerhistory.org/resources/access/text/2016/04/102738129-05-01-acc.pdf, accessed Sep. 18, 2018.

[11]Interview of G. D. Forney, Jr. by J. M. Pelkey, Jul. 28, 1988, CHM ref. no. X5671.2010, p. 6, http://archive.computerhistory.org/resources/access/text/2016/04/102738110-05-01-acc.pdf, accessed Aug. 31, 2018.

[12]G. D. Forney, Jr., "Maximum-likelihood sequence estimation of digital sequences in the presence of intersymbol interference," *IEEE Trans. Inf. Theory*, vol. IT-18, no. 3, pp. 363–378, May 1972.

chassis board. The "Forney Decoder," marketed and sold as the "Threshold Decision Computer," became a popular $2000 add-on, in part because Berner included a red indicator light that blinked when it corrected an error.[13] Ironically, customers began pulling out the TDC drawer so that they could see how frequently it improved the modem's performance.[14]

There remained the matter of sensitivity to "carrier phase jitter" on analog telephone lines. In single-sideband modems, phase jitter is transmitted as noise and "there really isn't much you can do about it." This was a phenomenon unique to the AE-96's high data rate, and neither Holsinger nor AT&T had anticipated it. Because the transmission properties of different lines varied from each other and over time, Codex engineers had to adjust customers' modems frequently. This was an expensive process on the trans-Atlantic links where Air France and British Overseas Airways had installed them, requiring coordinated effort by engineers on both ends.

For the better part of a year, Art Carr, Codex's vice president for marketing, had pushed for a 4800-b/s modem that worked without adjustments or add-ons like the Forney Decoder. Prospective modem customers balked at the AE-96, which, when it worked, provided more capacity than they needed. In a meeting in February 1970, he finally gained permission from Cryer to expand the company's tiny product line. Forney's support for a new modem aided Carr's cause through his suggestion for getting 4800 b/s on 1600 Hz of bandwidth, which would also solve the phase jitter issue: "I think I know how you could do that based on the Modem X kinds of ideas."[15]

This must have surprised the others, but Forney had been discussing the subject of quadrature amplitude modulation (QAM) transmission intermittently with Robert Gallager, Codex consultant and his MIT doctoral advisor. Over the previous year, Gallager had found that the single-sideband approach to modems made him "so frustrated with Hilbert transforms and the like that I said that there must be an easier way." The technique that Holsinger and others were following was more complicated mathematically than seemed necessary, which raised the theoretical alternative of "Modem X," using double-sideband QAM transmission instead. This "would be much easier, carrier and timing recovery would be much easier, and we could understand what we were doing."[16] Gallager "realized in general terms that by proper placement of the signal points, further apart in the phase direction than in the amplitude direction, that you could get increased immunity against phase jitter, and that was something that you could get inherently in the signal constellation."[17] Forney seized on Gallager's insight and "came up with the specific signal structures that we actually used, the eight-point structure for 4800 and [later]...16 points for 9600, which exploited that."[18] In addition, the new modem was "basically the same [MSI TTL, or medium-scale integration transistor-transistor logic] technology I...had learned about by designing this high-speed sequential decoder[19].... in '68 to '69...." But "the key to its success was that somebody who understood what needed to be done algorithmically was also doing all the digital design and could optimize the design. So it was much more reliable, much lower in factory cost, and a lot more modern...."

Also fortuitous was the expiration of the sequential decoder contract, although it hardly seemed that way at the time. "The contracting guy called me up in the early part of that year and said: 'Gee whiz, they wouldn't have the money after all.'" Consequently, Forney could devote his energies completely to Modem X. In February, all that he had was "just pencil and paper stuff, which was the way I preferred to work and Gallager preferred to work, but we fully understood what it entailed." It was not a simple process. Initially he put "in a different 8-point signal structure, which was unbalanced, asymmetrical. Gallager shook his head and said it was ugly. It was there specifically for the purpose of getting an analog carrier that you could track at the receiver with an analog phase-locked loop. I knew, in principle, that you could have a digital phase tracker based on the actual decision output of the modem, but I didn't trust it. About three months into the program... I remember all of a sudden being converted.... Gallager had been picking on me all the while, and I said, 'OK, we'll do it the digital way, convert it to this nice symmetrical eight-point signal structure, put in decision-directed phase-tracking.' It worked much better, actually, and... the whole modulation scheme was ripped out, reengineered, a new one put in about a week.... [I]t worked fine from the very beginning."[20]

While the company imploded around them, Forney's group focused on the task at hand. By May it had a breadboard demonstration of the 4800-b/s QAM modem; over the summer and fall, he was called on to demonstrate it periodically as executives sought buyers for the company. These included "a rubber company in Muskegon, which made retreaded tires," and Milgo, the leader in modems, but "they turned us down anyway."[21]

In September 1970, after months of borrowing for payroll every two weeks, Codex finally raised a million dollars in financing. Forney was promoted to vice president of

[13]Personal communication from G. D. Forney, Jr., Sep. 6, 2018.
[14]*Ibid.*, Interview of A. Carr, p. 6.
[15]Interview of G. D. Forney, p. 7.
[16]"Robert G. Gallager wins the 1999 Harvey Prize," *IEEE Inf. Theory Soc. Newslett.*, vol. 49, no. 3, p. 29, Sep. 1999.
[17]G. D. Forney, Jr. and R. Gallager, "Signal structures for double side band-quadrature carrier modulation," U.S. Patent 3,887,768, filed Sep. 14, 1971.
[18]Interview of G. D. Forney, p. 8.
[19]G. D. Forney, Jr. and E. K. Bower, "A high-speed sequential decoder: Prototype design and test," *IEEE Trans. Commun. Technol.*, vol. COM-19, pp. 821–835, 1971.
[20]Interview of G. D. Forney, p. 9.
[21]Interview of A. Carr, p. 9.

research and to the board of directors in a reorganization of management. Three months later at the Fall Joint Computer Conference, the 4800C made its debut. It was, in the words of marketing manager John Pugh, "absolutely phenomenal in terms of performance. We took that out on lines that nobody could run on, and that modem would run ten to the eighth. It would never make an error. . .. We just couldn't build it fast enough." After one successful demonstration, he told Forney, "'You know, this thing ran perfect.' And he said, 'What were the parameters?' And I told him, and he said well, 'Naturally. I would expect it to.' It was no surprise to him."[22]

For Forney, that was the beauty of information theory "in an area where paper-and-pencil design translated directly into real-world performance." He extended the 4800C's design to a 9600-b/s modem that Codex introduced in 1971. The C series "was much more reliable, much lower in factory cost, and a lot more modern in design. . .. I mean, we were the only people who had a 9600 b/s modem that actually worked reliably. And we had a bunch of customers for whom that was very important, so it was like shooting fish in a barrel."

Together with an optional multiplexer, the modems saved customers thousands of dollars on leased telephone lines for data transfer. Milgo and AT&T did not offer similar products until 1974, a delay that established Codex as the expanding industry's technical leader. The company doubled in size each of the next five years, and by 1980 Codex had sold its 50 000th 9600 modem, or more than 100 times the executive sales estimate considered laughable during the AE-96 debacle.[23] The 9600C modem also became the basis for the ITU V.29 international standard for 9600-b/s transmission over leased-line telephone circuits.[24]

II. MANAGING THE INNOVATION OF INFORMATION THEORY, 1972–1986

It was time for Forney to take a break. "After developing this new modem family I basically went 'Aaaggghhh,' and went off to Stanford for a year." Stanford proved, however, to be insufficiently alluring to stay in California and Forney returned to Codex late in 1972.

The innovation of modems had not stopped, in part because of the electronics trend driven by Moore's Law. Codex collaborated with Rockwell to develop a large-scale-integration (LSI) series of modems between 1973 and 1975. Although the companies' negotiators had agreed only to migrate the C series of MSI modems to LSI chips, Forney and his engineering team convinced their Rockwell counterparts to improve the circuitry. Introduced at *Datamation*'s Interface '76 conference, the new modems were not only much smaller and cooler than their predecessors and many competitors, they also featured "a fast startup mode for multipoint, there were different rate modes, there was a new equalization technique, and so forth"[25] (Fig. 1). Rockwell established itself as the dominant fax chip manufacturer, and sales of the L series cemented Codex's technical reputation while adding fuel to its growth.

Nonetheless, the company faced a fundamental threat to its existence. As the markets for digital communications grew, so did the competition. The biggest threat seemed to be not in competitors' modems, which lacked the theoretical grounding that Forney and his colleagues provided, but the national telephone monopoly. AT&T announced its Digital Data Service (DDS) early in 1975, offering private digital lines that portended the extinction of modems.[26] "We were scared to death. We honestly believed that we had maybe five more years in the modem business, and by then we damn well better be in some other business."

Beyond the commercial threat, Codex faced an apparent dead end technologically. The accepted truth among information theorists was "that theoretical and algorithmical development had gone as far as you could go, that 9,600 bits per second was as high as you could ever realistically get over the general telephone network." Forney recalled that "there was really nothing more to do, and in retrospect this is remarkable, because Shannon proved what the ultimate capacity of various channels is. Basically, a telephone line is fairly well modeled as a band-limited, point-to-point Gaussian noise channel. . . and it's very easy to calculate that. . . the traditional signal structures are something like 9 dB away from channel capacity. They're 6 dB away from a figure called R0, which is often taken as a practical theoretical limit on practical capacity. . .."[27]

To expand Codex's business into an area that would complement modems and survive into an era of digital networks, Forney hired James VanderMey, a computer scientist at the University of Illinois, to direct network product development in 1974. VanderMey immediately began developing a sophisticated statistical multiplexer based on an elegant multiple-microprocessor architecture. The complexity and ambition of the project tested the limits of Codex's technical and managerial capabilities, but the 6030 Intelligent Network Processor became the basis of a second, successful product line.[28]

[22]Interview of J. Pugh by J. Pelkey, Feb. 25, 1988, CHM ref. no. X5671.2010, p. 12, http://archive.computerhistory.org/resources/access/text/2016/03/102738098-05-01-acc.pdf, accessed Aug. 31, 2018.

[23]Interview of A. Carr, p. 14.

[24]ITU-T, "V.29 (11/1988) 9600 bits per second modem standardized for use on point-to-point 4-wire leased telephone-type circuits," extract from *The Blue Book: Telecommunication Policies for the Americas*, vol. VIII (Geneva, 1989), http://handle.itu.int/11.1002/1000/2749, accessed Sep. 5, 2018.

[25]Interview of G. D. Forney, p. 17. See also G. D. Forney, Jr. and J. C. Hart, U.S. Patent 3,978,407, "Fast start-up adaptive equalizer communication system using two data transmission rates," filed Jul. 23, 1975; and "Codex LSI modems feature 'gearshift' capability," *Computerworld*, p. 17, Dec. 17, 1975.

[26]"FCC oks first bell route to use data under voice," *Computerworld*, p. 17, Sep. 20, 1972.

[27]Interview of G. D. Forney, p. 25.

[28]*Ibid.*, p. 18–20; Interview of J. Pugh, pp. 24–27; Interview of A. Carr, p. 18–19.

Overseeing VanderMey's project, defending the QAM patent against Milgo[29], and rising in Codex's management kept Forney "completely out of the research business" for the next decade. In 1975, Forney agreed to lead the 200-person Research and Development Department, a major departure from heading the smaller Research Department. Two years later, Motorola, Inc., acquired Codex for $80 million.[30] As Codex's chief technical officer and a member of the board, Forney was deeply involved in the negotiations and then in integrating Codex into the far larger firm. The acquisition proved very successful for both parties, with little turnover in Codex personnel even as it grew by another order of magnitude over the next decade.

Meanwhile, Gottfried Ungerboeck of IBM Zurich Research Laboratory had been rethinking the approach to coding for bandwidth-limited channels. At a conference in Sweden in 1976, he and colleague Istvan Csajka proposed that 2-D trellis-coded modulation (TCM)—using the Viterbi algorithm and Forney's trellis concept—could provide another 3 dB of SNR on a bandwidth-limited channel, such as a telephone line.[31] Forney was scheduled to speak at the conference, but then unable to attend. He has never learned why "it took trellis-coded modulation so long to be recognized as the extraordinarily valuable and practical technique that it was." He "was in a modem company, and could fully appreciate what the advantages of it could be. The biggest mystery is, why did I miss this?"

The consolations were that he was not alone in the modem community and that, given the breadth of his responsibilities, Forney could "at least give myself the excuse that when Gottfried buttonholed me I just wasn't thinking about getting a few more dB." In 1982, when Ungerboeck finally published his paper,[32] Motorola created a new Information Systems Group (ISG) to oversee Codex and several other data communications companies that it had acquired or spun off, and made Forney its Vice President and Director of Technology and Planning. For the next four years, during which Forney established and integrated the ISG's place in the corporation, he also began to return to the field of modem technology.

By 1983, the Comité Consultatif International Téléphonique et Télégraphique (CCITT) had begun considering TCM for its V.32 standard for 9600 dial-up modems. Forney was instrumental in promoting Ungerboeck's approach to CCIT members while alerting him to their interest, after which Ungerboeck and IBM participated in setting the standard.[33] Forney's political insight and technical perspicacity rewarded Codex as the CCITT settled on a 2-D form of TCM. "When it all of a sudden became hot, we were prepared. We... had five different ways we could go...." Codex's engineers "picked an appropriate scheme that ultimately was the scheme that CCITT adopted, so we were the first to market with a trellis-coded modem, in '84... since it was pretty well known what way it was going to go by that time."[34]

Forney and Codex compounded the return on their grasp of the new technique with the hire of Lee-Fang Wei, "an incredibly productive, hard-working, bright engineer," from AT&T. Building on his previous work, and Forney and Gallager's "simple" multi-dimensional constellations,[35] Wei worked out some "very implementable multi-dimensional schemes" that superseded V.32's 2-D TCM. These resulted in the 2680, the first practical 19 200-b/s modem, in 1985.[36] Codex sold 100 000 of its 2600 modem series in three years, controlling some 44% of the American leased-line modem market.[37] The revenues from leased-line modems comprised more than half of Codex's domestic income and just under half of its international income in 1986–1987.[38]

III. RETURNING TO RESEARCH, 1986–2018

Forney returned to Codex in 1986 as a Motorola Vice President of the Technical Staff, having made it known that he would "just like to be a little technical for a while."[39] Subsequently he once again became deeply involved in modem technology, and a prolific contributor to the information theory literature. What more was there after the doubling of modem capacity over telephone lines in five

[29]For more on the Codex-Milgo/Racal patent dispute, see Interview of G. D. Forney, pp. 12–15; Interview of J. Pugh, pp. 14–17; and Interview of A. Carr, pp. 29–31.

[30]J. Pelkey, *Entrepreneurial Capitalism and Innovation: A History of Computer Communications, 1968–1988*, Ch. 5, Sec. 5.15 "Codex and Motorola 1977–1978," www.historyofcomputercommunications.info/Book/5/5.11CodexMotorola77-78.html, accessed Sep. 11, 2018.

[31]G. Ungerboeck and I. Csajka, "On improving data link performance by increasing the channel alphabet and introducing sequence coding," *Proc. 1976 Int. Symp. Inf. Theory (ISIT)*, Ronneby, Sweden, Jun. 1976; and "On improving data-link performance by increasing the channel alphabet and introducing sequence coding," in H. Crowder, ed., *1976 IBM Symposium on Mathematics and Computation*, Yorktown Heights, NY, USA: Oct. 6–8 1976, pp. 194–205; I. P. Csajka and G. Ungerboeck, U.S. Patent 4,077,021, "Method and arrangement for coding binary signals and modulating a carrier signal," filed Jun. 18, 1976. See also G. Ungerboeck, an oral history conducted in 2004 by F. Nebeker, IEEE History Center, Hoboken, NJ, USA, https://ethw.org/Oral-History:Gottfried_Ungerboeck.

[32]G. Ungerboeck, "Channel coding with multilevel/phase signals, *IEEE Trans. Inf. Theory* vol. 28, no. 1, pp. 55–67, Jan. 1982.

[33]Interview of G. D. Forney, pp. 22–23.

[34]Ibid., p. 26, p. 22.

[35]L.-F. Wei, U.S. Patent 4,483,012, "Differentially convolutional channel coding with expanded set of signalling alphabets," filed Apr. 18, 1983; *idem*, U.S. Patent 4,520,490, "Differentially nonlinear convolutional channel coding with expanded set of signalling alphabets," filed Aug. 5, 1983; R. G. Gallager, U.S. Patent 4,700,349, "Coded modulation system," filed Feb. 6, 1984; G. D. Forney, Jr., U.S. Patent 4,597,090, "Block coded modulation system," filed Apr. 14, 1983.

[36]L.-F. Wei, U.S. Patent 4,713,817, "Multidimensional, convolutionally coded communication systems," filed Apr. 25, 1985; L.-F. Wei, "Trellis-coded modulation with multidimensional constellations," *IEEE Trans. Inf. Theory*, vol. IT-33, no. 4, pp. 483–501, Jul. 1987; "Codex modem adds error-correcting data," *Micro Marketworld*, vol. 8, no. 22, p. 92, Nov. 1985.

[37]Interview of G. D. Forney, p. 15; Pelkey, *Entrepreneurial Capitalism*, Ch. 12, Sec. 12.15 "Codex," www.historyofcomputercommunications.info/Book/12/12.15_Codex.html, accessed Sep. 8, 2018.

[38]Based on Pelkey, Ch. 12, Exhibit 12.13—Codex Forecasted Revenue 1987, www.historyofcomputercommunications.info/Book/12/12.15_Codex.html, accessed Sep. 13, 2018.

[39]Personal communication from G. D. Forney, Jr., Sep. 18, 2018.

years? [40] "How far can this evolution go?" Forney and his ISG coauthors asked in the first of Forney's articles after a seven-year lull. "History would suggest caution in stipulating any ultimate ceiling." On the one hand, "without any dramatic general upgrading of the telephone network, we venture to say that 19.2 kbits/s is the maximum conceivable rate for a telephone-line modem for general use, even without all-out use of the most powerful coded modulation." On the other, "We shall see."[41]

Twelve years later, after successfully advocating for multidimensional TCM and other advanced techniques in the ITU V.34 standard for modem data transmission, Forney knew better than to join the chorus of observers claiming that 33 600 b/s was the ultimate modem rate for general switched telephone networks, or that "V.fast = V.last."[42] In his Claude E. Shannon Award speech to the IEEE Information Theory Society in 1995, he had observed that "every two years the boundary between 'feasible' and 'infeasible' advances by another factor of two." That advance, like those popularly lumped under Moore's Law, was a product of engineering, "in which elegant theory is motivated by practical problems and so often leads to practical advances. . . . [R]esearch based on hard metrics of performance and complexity often yields the best theory as well as the best applications."[43]

Forney took this philosophy back to MIT in 1996 as the Bernard M. Gordon Adjunct Professor, where he continued to research and write prodigiously on an array of subjects in information theory (Fig. 2). Between 1988 and 2017, he published 75 articles, often collaborating with an international array of colleagues and twice winning the IEEE Donald G. Fink Paper Award for the outstanding survey, review, or tutorial paper in any IEEE publication.[44]

In the early 2000s, a group of researchers, most of who had worked for Forney at Codex and Motorola, extended the international standard for data transmission over standard telephone networks. In enabling up to 48 000 b/s on analog upstream signalling rates to complement the digital downstream rates of 56 000 b/s,[45] they raised the question, again, of whether their job was done. Although they predicted in the abstract "that V.92 will be the last dial-up modem standard," the question remained "whether we might be falling into the same trap into which many others have fallen in the past."[46]

Fig. 2. *MIT's Bernard M. Gordon Adjunct Professor G. David Forney, Jr. (Courtesy of LIDS.)*

In 2009, in concluding a magisterial, award-winning tour of the evolution of channel coding, Daniel J. Costello, Jr., and Forney raised a broader question. Echoing an infamous debate at the first IEEE Communication Theory Workshop in 1971, they asked, "So is coding theory finally dead?" After all, mathematicians, engineers, and scientists had used old and new techniques to bring the transmission of information within 1 dB of the Shannon limit on classical communication channels, while making similar inroads in wireless and internet communications. Nearly 50 years after first exploring Léon Brillouin's study of information theory[47] as an undergraduate, however, Forney, together with Costello, was ready to take the long and optimistic view: "Research motivated by issues of performance vs. complexity will always be in fashion. . . . Coding for nonclassical channels, such as multi-user channels, networks, and channels with memory, are hot areas today that seem likely to remain active for a long time. The world of coding research thus continues to be an expanding universe."[48] One imagines that Brillouin, and Shannon, would be pleased. ■

[40]Paradyne Corporation introduced the first generation of 14 400-b/s modems in 1981: G. D. Forney, Jr., *et al.*, "Efficient modulation for band-limited channels," *IEEE J. Sel. Areas Commun.*, vol. SAC-2, no. 5, p. 632, Sep. 1984. (Reprinted in W. H. Tranter *et al.*, *The Best of the Best: Fifty Years of Communications and Networking Research*. New York, NY, USA: Wiley–IEEE Press, 2007, p. 157.)

[41]Forney *et al.*, "Efficient modulation for band-limited channels," *IEEE J. Sel. Areas Commun.*, vol. 2, no. 5, pp. 632–633, Sep. 1984.

[42]G. D. Forney, Jr., *et al.*, "The V.34 high-speed modem standard," *IEEE Commun. Mag.*, Dec. 1996, p. 33.

[43]ITU V.34 (02/98), "A modem operating at data signalling rates of up to 33 600 bit/s for use on the general switched telephone network and on leased point-to-point 2-wire telephone-type circuits," www.itu.int/rec/T-REC-V.34/en, accessed Sep. 14, 2018. G. D. Forney, Jr., "Performance and complexity," *IEEE Inf. Theory Soc. Newslett.*, pp. 3–5, Mar. 23–25, 1996. For a recent survey of the triumphs of and obstacles to Moore's Law, see I. Markov, "Limits on fundamental limits to computation," *Nature* vol. 512, pp. 147–154, Aug. 14, 2014.

[44]The bulk of these can be found on Google Scholar, whose citation count totaled 29 194 as of Sep. 14, 2018: https://scholar.google.com/scholar?hl=en&as_sdt=0%2C31&as_vis=1&q=%22g+david+forney%22&btnG=.

[45]ITU-T, "V.92: Enhancements to Recommendation V.90: Recommendation V.92 (11/00)," www.itu.int/rec/T-REC-V.92-200011-I/en, accessed Jun. 14, 2018.

[46]D.-Y. Kim *et al.*, "V.92: The last dial-up modem?" *IEEE Trans. Commun.*, vol. 52, no. 1, p. 54, Jan. 2004.

[47]L. Brillouin, *Science and Information Theory*. New York, NY, USA: Academic, 1956; 2nd ed. 1962. As IBM's director of electronic education, Brillouin wrote an early article on coding: "Information theory and most efficient codings for communication or memory devices," *J. Appl. Phys*, vol. 22, no. 9, pp. 1108–1111, 1951.

[48]D. J. Costello, Jr., and G. D. Forney, Jr., "Channel coding: The road to channel capacity," *Proc. IEEE*, vol. 95, no. 6, p. 1174. For the 1971 Workshop debate, see p. 1158; and for Forney's early perspective on that debate and the future of information theory, see his "Editorial" in *IEEE Trans. Inf. Theory*, vol. IT-19, no. 1, p. 2, Jan. 1973.

Acknowledgments

The author would like to thank Prof. Forney for his thoughtful review and corrections, additional information, and suggestions; and J. Pelkey for his singular online book and website, "A History of Computer Communications, 1968–1988," www.historyofcomputercommunications.info/index.html. Its immense resources, particularly the oral histories that he recorded and transcribed, were invaluable to the writing of this article. Any remaining errors of fact or interpretation are the author's responsibility.

ABOUT THE AUTHOR

Alexander B. Magoun grew up in Manchester, MA, USA. He received the B.A. degree in history from Trinity College, Hartford, CT, USA, the M.A. degree in history from the University of East Anglia, Norwich, U.K., and the Ph.D. degree in American history from the University of Maryland, College Park, MD, USA.

Currently, he is the Outreach Historian for the IEEE History Center at Stevens Institute of Technology, Hoboken, NJ, USA and Associate Editor for History for the PROCEEDINGS OF THE IEEE. Before joining the IEEE History Center, he was Executive Director of the David Sarnoff Library, Princeton, NJ, USA. He is the author of *David Sarnoff Research Center: From RCA Laboratories to Sarnoff Corporation* (2003), *Television: Life Story of a Technology* (2007), and several articles in the PROCEEDINGS OF THE IEEE. His research interests have included the innovation process in analog disc records, David Sarnoff and RCA, television, early wireless telegraphy, the electrification of Frankenstein, and the roles of engineers in creating the world's great powers.

Dr. Magoun is a member of the Society for the History of Technology and the New Jersey Antique Radio Club. He was honored recently with the 2018 IEEE Region 1 Enhancement of the IEEE or Engineering Profession's Image with the Public Award.